

The effect of radiative cooling on scaling laws of X-ray groups and clusters

Article (Published Version)

Muanwong, O, Thomas, P A, Kay, S T, Pearce, F R and Couchman, H M P (2001) The effect of radiative cooling on scaling laws of X-ray groups and clusters. *Astrophysical Journal*, 552 (1). pp. 27-30. ISSN 0004-637X

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/24407/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

THE EFFECT OF RADIATIVE COOLING ON SCALING LAWS OF X-RAY GROUPS AND CLUSTERS

O. MUANWONG¹, P. A. THOMAS¹, S. T. KAY¹, F. R. PEARCE² AND H. M. P. COUCHMAN³
Draft version January 13, 2014

ABSTRACT

We have performed cosmological simulations in a Λ CDM cosmology with and without radiative cooling, in order to study the effect of cooling on the cluster scaling laws. Our simulations consist of 4.1 million particles each of gas and dark matter within a box-size of $100 h^{-1}$ Mpc and the run with cooling is the largest of its kind to have been evolved to $z = 0$. Our cluster catalogues both consist of over 400 objects and are complete in mass down to $\sim 10^{13} h^{-1} M_{\odot}$. We contrast the emission-weighted temperature-mass ($T_{\text{ew}} - M$) and bolometric luminosity-temperature ($L_{\text{bol}} - T_{\text{ew}}$) relations for the simulations at $z = 0$. We find that radiative cooling increases the temperature of intracluster gas and decreases its total luminosity, in agreement with the results of Pearce et al. Furthermore, the temperature dependence of these effects flattens the slope of the $T_{\text{ew}} - M$ relation and steepens the slope of the $L_{\text{bol}} - T_{\text{ew}}$ relation. Inclusion of radiative cooling in the simulations is sufficient to reproduce the observed X-ray scaling relations without requiring excessive non-gravitational energy injection.

Subject headings: galaxies: clusters: general, cosmology: theory

1. INTRODUCTION

The mass of clusters of galaxies⁴ is dominated by dark matter. The evolution of the dark matter halo population is now well-understood both theoretically (Lacey & Cole 1994) and numerically (Jenkins et al. 2001). The halos themselves are approximately self-similar and may be described in their inner regions by a one-parameter model (Navarro, Frenk & White 1997) with a concentration parameter that is a slow function of mass. (Note, however, that there are significant deviations from this simple profile in the outer parts of clusters; see Thomas et al. 2001.)

The intracluster medium (ICM) does not share the approximate self-similarity of the dark matter. This is expressed most clearly in the X-ray luminosity-temperature relation. For pure bremsstrahlung emission, the bolometric X-ray luminosity should scale with temperature as $L_{\text{x}} \propto T_{\text{x}}^2$ (the inclusion of line emission flattens this relation), whereas observations indicate a much steeper temperature dependence, especially for low-mass systems (Edge & Stewart 1991; David et al. 1993; Ponman et al. 1996; White, Jones & Forman 1997; Xue & Wu 2000). At high temperatures part of this steepening is due to a central cooling flow, but removing the cooling flow component still does not reconcile the observations with the self-similar prediction (Allen & Fabian 1998; Markevitch 1998).

The reason for the departure from self-similarity is that the gas is not as centrally-concentrated in clusters as the dark matter, which is best physically expressed as an increase in entropy of the innermost gas (Evrard & Henry 1991; Kaiser 1991; Bower 1997). The most obvious explanation for this is that there has been some form of energy injection. The amount of energy required depends upon the density of the gas at the time when the heating occurred. Lloyd-Davies, Ponman & Cannon (2000) argue for heating prior to cluster collapse and estimate a value of 0.3 keV per particle. Tozzi & Norman (2001) show that this can be lowered to 0.1 keV per particle by heating at

the optimal time (when the gas is at its minimum density) but most other studies that consider heating within collapsed halos require much higher values of 1–3 keV per particle (Wu, Fabian & Nulsen 2000; Bower et al. 2000; Lowenstein 2000).

There are two likely sources for any excess energy: stellar winds/supernovae and active galactic nuclei (AGN). It is known for CDM models that some feedback of energy into the intergalactic medium must occur in order to prevent the “cooling catastrophe”, in which the majority of the baryons in the Universe cool and form stars at high redshift (White & Frenk 1991; Cole 1991; Blanchard, Valls-Gabaud & Mamon 1992). If the heating efficiency is high, supernovae can inject an energy of order 0.3 keV per particle into the intergalactic medium, but they do not do so in an optimal way. Various authors, all of whom consider realistic, but different, models for the build-up of structure, conclude that supernovae are unable to provide the required excess entropy (Valageas & Silk 1999; Wu, Fabian & Nulsen 2000; Bower et al. 2000). Heating of the intergalactic medium by quasars is also not without its problems as the heating must occur at just the right time in order not to overly suppress galaxy formation. Alternatively, the heating may arise from AGN buried within individual galaxies (Bower et al. 2000).

Radiative cooling results in the removal of low-entropy gas in the cluster core and thus leads to an overall increase in temperature of the ICM (Thomas & Couchman 1992). The amount of cooling that takes place in a cooling flow after the final assembly of a cluster is insufficient to explain the observations (Bower et al. 2000), but a more realistic model in which cooling occurs at every stage of the collapse hierarchy can give entropy increases equivalent to an excess energy of 1–2 keV per particle (Wu, Fabian & Nulsen 2000)—in essence most of the cooling occurs in galaxy-sized halos before the formation of the cluster. Bryan (2000) has developed a simple model in which low-entropy gas is removed from the cluster core and the surrounding gas is assumed not to have cooled at all. Al-

¹ Astronomy Centre, University of Sussex, Falmer, Brighton, BN1 9QJ, U.K.; O.Muanwong@sussex.ac.uk, P.A.Thomas@sussex.ac.uk, S.T.Kay@sussex.ac.uk

² Dept. of Physics, University of Durham, South Road, Durham, DH1 3LE, U.K.; F.R.Pearce@durham.ac.uk

³ Dept. of Physics, McMaster University, Hamilton, Ontario, L8S 4M1, Canada; couchman@physics.mcmaster.ca

⁴ Throughout this paper we will not distinguish between groups and clusters of galaxies but will use the term clusters to stand for both

though this model has obvious deficiencies, it predicts the correct luminosity-temperature relation from 0.5–10 keV.

Simulations of cluster formation including radiative energy loss have been carried out by Pearce et al. (2000). They showed that the gas is slightly heated and that the luminosity is greatly reduced (except in cooling flow clusters), in agreement with expectations. However, the simulations were of limited resolution and covered only a small range in cluster mass. We are now undertaking a programme of simulations to extend these results over a wider mass-range and to contrast the properties of clusters in different cosmologies. In this letter we report results at $z = 0$ from two simulations of a $100 h^{-1} \text{Mpc}$ box in the ΛCDM cosmology, one with and one without radiative cooling.

The simulations and cluster extraction method are described in Section 2 and the results are presented in Section 3. We summarize our conclusions in Section 4.

2. METHOD

2.1. The simulations

We have carried out two simulations with 160^3 particles each of gas and dark matter within cubical volumes of side $100 h^{-1} \text{Mpc}$. The cosmological parameters were as follows: density parameter, $\Omega_0 = 0.35$; cosmological constant, $\Lambda_0 = \Lambda/3H_0^2 = 0.65$; Hubble parameter, $h = H_0/100 \text{km s}^{-1} \text{Mpc}^{-1} = 0.71$; baryon density parameter, $\Omega_b h^2 = 0.019$; power spectrum shape parameter, $\Gamma = 0.21$; and a linearly-extrapolated root-mean-square dispersion of the density fluctuations on a scale $8 h^{-1} \text{Mpc}$, $\sigma_8 = 0.90$. With these parameters, the gas and dark matter particle masses are approximately 2.6×10^9 and $2.1 \times 10^{10} h^{-1} M_\odot$, respectively. This mass is below the Steinmetz & White (1997) limit above which numerical heating dominates cooling. The runs were started at a redshift, $z = 50$ and evolved to the present day, $z = 0$. The gravitational softening was fixed at $50 h^{-1} \text{kpc}$ in comoving co-ordinates until $z = 1$ and thereafter held constant at $25 h^{-1} \text{kpc}$ in physical co-ordinates. This softening is sufficient to prevent two-body relaxation (Thomas et al. 2001) and we have checked that the gas and dark-matter have similar specific energy profiles in clusters drawn from the non-radiative simulation.

The only difference in the two runs was that one of them included radiative cooling. For this run, we used the cooling tables of Sutherland & Dopita (1993) and assumed a uniform but time-varying metallicity of $Z = 0.3(t/t_0)Z_\odot$, where t/t_0 is the age of the Universe in units of the current time. This time-varying metallicity is meant to crudely mimic the gradual enrichment of the ICM by stars, but more importantly it results in a global cooled gas fraction at the end of the simulation of approximately 20 per cent. This is the maximum value inferred from the observations of clusters (Balogh et al. 2001) which means that our simulation will represent the largest effect that cooling alone is likely to have on the intracluster medium.

We use a parallel version of the HYDRA N -body/SPH code as described by Couchman, Thomas & Pearce (1995) and Pearce & Couchman (1997) except that the SPH equations have been modified to use the pairwise artificial viscosity of Monaghan & Gingold (1983)—for a test of different SPH formalisms see Thacker et al. (2000). We decouple the hot and cold gas in the manner described by Pearce et al. (1999, see also Ritchie & Thomas 2001) to prevent artificial overcooling of hot gas onto the central cluster galaxies. Groups of 13 or more cold, dense gas particles (with $\delta > 500$ and $T < 12000 \text{K}$) are merged together to form collisionless *galaxy* particles, which can only

grow via the accretion of more gas. Not only does this save considerable computational effort, it also prevents small objects from being artificially disrupted within cluster potentials.

2.2. The cluster catalogue

Initially we identify clusters in our simulation by searching for groups of dark matter particles within an isodensity contour of 200, as described in Thomas et al. (1998). We work with a preliminary catalogue of all objects with more than 250 particles, then retain only those which have a total mass within the virial radius exceeding $M_{\text{lim}} \approx 1.18 \times 10^{13} h^{-1} M_\odot$, corresponding to 500 particles of each species. The use of a small mass for the preliminary cluster selection ensures that our catalogue is complete. We have checked that using a different isodensity threshold, a different selection algorithm, or using gas particles instead of dark-matter particles to define the cluster, leads to an almost identical cluster catalogue—the only difference being the merger or otherwise of a small number of binary clusters.

We define the centre of the cluster to be the position of the densest dark matter particle. Because the density parameter of the real universe is not known, we choose to average properties of the clusters within spheres that enclose an overdensity of 200 relative to the critical density (whereas for this cosmology the virial radius corresponds to an overdensity relative to critical of about 110). Our final catalogues consist of 427 and 428 clusters in the radiative and non-radiative simulations, respectively.

2.3. Cluster X-ray properties

We calculate the bolometric luminosity of each cluster using

$$L_{\text{bol}} = \sum_i \frac{m_i \rho_i}{(\mu m_{\text{H}})^2} \Lambda(T_i, Z), \quad (1)$$

where the subscript i denotes the sum over all gas particles within radius r_{200} that have temperatures, $T_i > 10^5 \text{K}$, masses m_i and densities, ρ_i ; we assume a mean molecular mass $\mu m_{\text{H}} = 10^{-24} \text{g}$ and an emissivity, $\Lambda(T_i, Z(t))$, that is the same function used by HYDRA to calculate cooling rates, as discussed in Section 2.1. Note that, for temperatures below about 10^7K , line emission is important and the cooling rates are substantially higher than the contribution from bremsstrahlung alone.

The emission-weighted temperature of each cluster is calculated as

$$T_{\text{ew}} = \frac{\sum_i m_i \rho_i \Lambda(T_i, Z) T_i}{\sum_i m_i \rho_i \Lambda(T_i, Z)}. \quad (2)$$

Many of the smaller clusters in our catalogues have emission-weighted temperatures that are below 0.5 keV which means that the majority of their emission will emerge at energies that are below the X-ray bands. We do not attempt to calculate the emission in any particular X-ray passband in this paper but instead quote bolometric luminosities and emission-weighted temperatures.

3. RESULTS

3.1. Temperature-mass relations

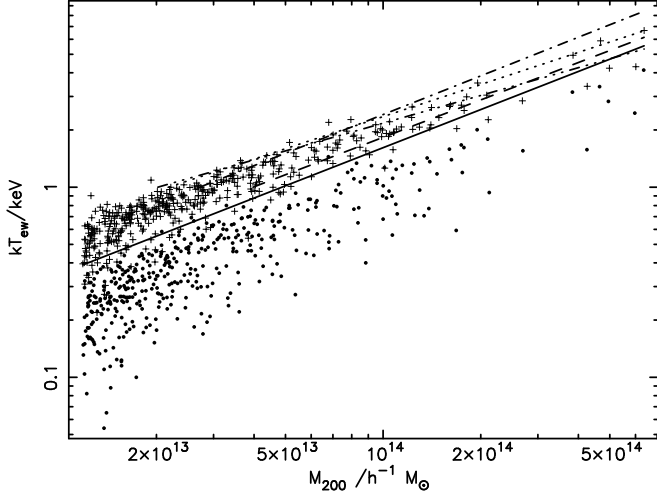


FIG. 1.— The emission-weighted temperature versus (total) mass within a density contrast of 200. Crosses and filled circles represent clusters from the simulations with and without radiative cooling, respectively. The various lines are described in the text.

We plot the emission-weighted temperature-mass relation for both cluster samples in Fig. 1. Results from the simulations with and without cooling are illustrated using crosses and filled circles, respectively. The broken lines are power-law fits to the observational relation as determined by Horner et al. (1999), using mass estimates from galaxy velocity dispersions (dashed), X-ray temperature profiles (dash-dotted), the isothermal β -model (dotted) and the surface brightness deprojection method (dash-triple dotted).

For the simulation with radiative cooling the relationship between T_{ew} and M is an approximate power law

$$kT_{ew} = 1.91 \left(\frac{M_{200}}{10^{14} h^{-1} M_{\odot}} \right)^{0.58} \text{ keV}, \quad (3)$$

and for the simulation without radiative cooling

$$kT_{ew} = 0.98 \left(\frac{M_{200}}{10^{14} h^{-1} M_{\odot}} \right)^{0.67} \text{ keV}. \quad (4)$$

These should be compared with the virial relation (shown as the solid line on the figure)

$$kT_{vir} = 1.61 \left(\frac{M_{200}}{10^{14} h^{-1} M_{\odot}} \right)^{0.67} \text{ keV}. \quad (5)$$

(Note that no attempt has been made when making these fits to reproduce the observational selection effects. They should therefore be regarded as rough guides rather than precise predictions.) The clusters from the non-cooling run mostly have emission-weighted temperatures that are much lower than the virial values. The reason for this is that their emission is dominated by high-density, low-temperature gas in the core of the cluster (this temperature drop in the core is simply due to the fact that the specific energy profile of the gas mimics that of the dynamically-dominant dark matter). Small fluctuations in the core properties of the clusters (which are not well-resolved by our simulations) lead to a large scatter in predicted temperatures. It is important to note that these non-radiative simulations do not provide sensible predictions for the observed properties of real clusters—the core gas has a short cooling time and would not in reality persist in the intracluster medium for the lifetime of the cluster.

We note that our non-radiative $T_{ew} - M$ relation has a lower normalization than found by Thomas et al. (2001) for simulations in the τ CDM cosmology because there it was assumed that the emission is purely bremsstrahlung, which underestimates cooling rates below 10^7 K and places less weight on the innermost region of clusters.

In contrast to the non-radiative run, the clusters from the radiative simulation have emission-weighted temperatures that show less scatter and that exceed the virial values. The reason for this is that the core gas has cooled to low temperatures and been removed from the intracluster medium, leaving behind higher-entropy, higher-temperature gas—an effect that is more pronounced in lower-mass clusters. The emission is no longer dominated by the core and is well-resolved by our simulations. The clusters provide an adequate fit to the observational data given the large uncertainty in the latter as evidenced by the various broken lines in Fig. 1.

3.2. Luminosity-temperature relations

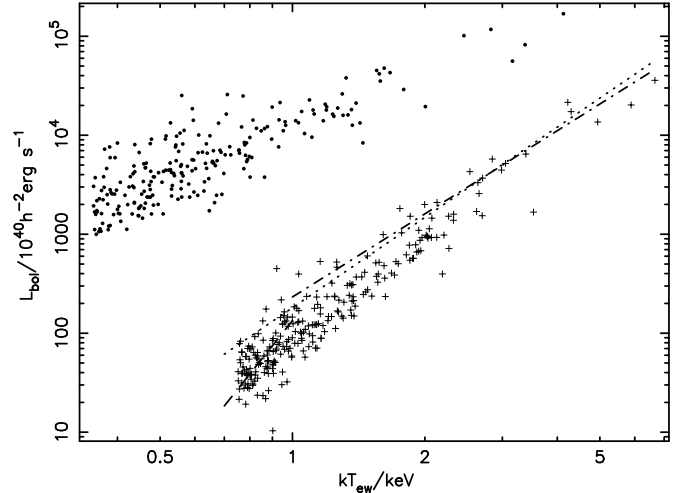


FIG. 2.— The bolometric luminosity-temperature relations for our simulations. Clusters are represented by the same symbols used in Fig. 1 and broken lines represent the fits to observational data by Xue & Wu (2000).

Fig. 2 illustrates X-ray luminosity-temperature relations for both simulations, again using crosses and filled circles for radiative and non-radiative clusters respectively. We have trimmed the original catalogues by selecting clusters only with temperatures above 0.35 and 0.75 keV for the non-radiative and radiative cooling catalogues respectively, to assure completeness in temperature. The broken lines illustrate best-fit power-law relations as determined by Xue & Wu (2000) for their collected group sample (dashed line), cluster sample (dot-dashed line) and combined sample (dotted line). (Note that the units for the normalisation of the relations in Table 2 of Xue & Wu 2000 are misquoted and should be a factor of 10 larger, in agreement with their Table 1 and Figure 1.)

A power-law fit to results from the radiative simulation gives

$$L_{bol} = 9.0 \times 10^{41} \left(\frac{T_{ew}}{1 \text{ keV}} \right)^{3.3} h^{-2} \text{ erg s}^{-1}, \quad (6)$$

and for the non-radiative simulation

$$L_{bol} = 1.2 \times 10^{44} \left(\frac{T_x}{1 \text{ keV}} \right)^{1.9} h^{-2} \text{ erg s}^{-1}. \quad (7)$$

(As stated in section 3.1, these fits should not be taken as precise calibrations.) Again, both the slope and normalization

differ between the two simulations. The non-radiative simulation gives a slope close to 2, as predicted by self-similar scaling relations (the relation is slightly flatter due to the inclusion of line emission). However, the radiative simulation gives a significantly steeper slope of 3.3. The normalization of the relation is around a factor of 10–100 lower in the radiative simulation than in the non-radiative simulation. Qualitatively, these differences are the same as were found by Pearce et al. (2000), for a smaller cluster sample. The high entropy gas that replaces cooled material in the radiative simulation is hotter and less dense than the gas in the non-radiative simulation. The change in density has the greater effect, since the X-ray emissivity is a slow function of temperature but is proportional to the square of the gas density. The combination of the increase in temperature and the decrease in luminosity of the clusters causes the substantial shift in the $L_{\text{bol}} - T_{\text{ew}}$ relation.

The results from the radiative simulation are in good agreement with the best-fit relations of Xue & Wu (2000). If anything, we predict luminosities that are a factor of 2–3 too low, although there is still significant uncertainty in the observational determinations.

4. CONCLUSIONS

In this letter, we have presented results from an ongoing programme to measure the evolution of X-ray cluster properties for a range of physical and cosmological models. Specifically, we have presented the current-day ($z = 0$) emission-weighted temperature-mass ($T_{\text{ew}} - M$) and bolometric luminosity-temperature ($L_{\text{bol}} - T_{\text{ew}}$) relations from two simulations of a Λ CDM cosmology, one with and one without radiative cooling.

The $T_{\text{ew}} - M$ relation is significantly different in non-radiative and radiative simulations, with the latter in reasonable agreement with observational determinations. In the non-cooling simulation, the emission is dominated by cold, dense gas in the cores of the clusters; radiative cooling removes this gas from the intracluster medium (converting it into stars) and replaces it with higher-entropy, hotter material. This effect is more prevalent in lower-mass systems and so flattens the temperature-mass relation.

The $L_{\text{bol}} - T_{\text{ew}}$ relation is also significantly different between

the two simulations. The high entropy material in the radiative simulation is less dense than the material it replaces and causes the X-ray luminosity of clusters to decrease by around a factor of 100 at $T_{\text{ew}} = 1$ keV. The slope of the relation in the non-radiative simulation is 1.9, similar to self-similar predictions. However, the slope of the radiative relation is significantly steeper, 3.3, again due to the differential effect of cooling with halo temperature. The radiative simulation is in much closer agreement with the observations, both in the slope and normalization of the relation.

In this paper, we have used bolometric luminosities and emission-weighted temperatures. For the low-temperature clusters found in the non-radiative simulations, these will differ significantly from properties measured in any particular X-ray band. However, we wish to emphasize that to attempt to correct for this is misleading as the use of such simulations is wrong in principle—the low-entropy gas in the cores of these clusters has a short cooling time and will not be present in real systems.

The global fraction of cooled gas (and stars) in the radiative simulation, 20 per cent, is higher than suggested by observations of the K -band galaxy luminosity function (Balogh et al. 2001). More importantly, the fraction of cooled gas within the clusters varies between about one-third and two-thirds with decreasing mass. While these values are not convincingly ruled out by observations, most people would also regard these as high values—in which case our simulation can be treated as an upper bound on the effect of radiative cooling.

In this paper, we have deliberately ignored the effect of non-gravitational heating upon the gas. In reality, we know that there must be heating associated with star-formation and metal-enrichment of the intracluster medium. This will raise the entropy of the gas and reduce the amount of cooling that is required to match the observations. However, we do not regard the case for significant heating by AGN or very efficient supernovae feedback as proven.

The simulations described in this paper were carried out on the Cray-T3E at the Edinburgh Parallel Computing Centre as part of the Virgo Consortium investigations of cosmological structure formation. OM is supported by a DPST Scholarship from the Thai government; PAT is a PPARC Lecturer Fellow.

REFERENCES

- Allen S. W., Fabian A. C., 1998, *MNRAS*, 297, L57
 Balogh M. L., Pearce F. R., Bower R. G., Kay S. T., 2001, *MNRAS*, submitted
 Blanchard A., Valls-Gabaud D., Mamon G. A., 1992, *A&A*, 264, 365
 Bower R. G., 1997, *MNRAS*, 288, 355
 Bower R. G., Benson A. J., Baugh C. M., Cole S., Frenk C. S., Lacey C. G., 2000, *MNRAS*, in press (astro-ph/0006109)
 Bryan G. L., 2000, *ApJ*, 544, L1
 Cole S., 1991, *ApJ*, 367, 45
 Couchman H. M. P., Thomas P. A., Pearce F. R., 1995, *MNRAS*, 452, 797
 David L. P., Slyz A., Jones C., Forman W., Vrtilik S. D., 1993, *ApJ*, 412, 479
 Edge A. C., Stewart G. C., 1991, *MNRAS*, 252, 414
 Evrard A. E., Henry J. P., 1991, *ApJ*, 383, 95
 Horner D. J., Mushotzky R. F., Scharf C. A., 1999, *ApJ*, 520, 78
 Jenkins A., Frenk C. S., White S. D. M., Colberg J. M., Cole S., Evrard A. E., Couchman H. M. P., Yoshida N., 2001, *MNRAS*, 321, 372
 Kaiser N., 1991, *ApJ*, 383, 104
 Lacey C., Cole S., 1994, *MNRAS*, 271, 676
 Lloyd-Davies E. J., Ponman T. J., Cannon D. B., 2000, *MNRAS*, 315, 689
 Lowenstein M., 2000, *ApJ*, 532, 17
 Markevitch M., 1998, *ApJ*, 504, 27
 Monaghan J. J., Gingold R. A., 1983, *J. Comp. Phys.*, 52, 375
 Navarro J. F., Frenk C. S., White S. D. M., 1997, *ApJ*, 490, 493
 Pearce F. R., Couchman H. M. P., 1997, *New Astron.*, 2, 411
 Pearce F. R. et al. (the Virgo Consortium), 1999, *ApJ*, 521, L99
 Pearce F. R., Thomas P. A., Couchman H. M. P., Edge A. C., 2000, *MNRAS*, 317, 1029
 Ponman T. L., Bourner P. D. J., Ebeling H., Böhringer H., 1996, *MNRAS*, 283, 690
 Ritchie B. W., Thomas P. A., 2001, *MNRAS*, in press (astro-ph/0005357)
 Steinmetz M., White S. D. M., 1997, *MNRAS*, 288, 545
 Sutherland R. S., Dopita M. A., 1993, *ApJS*, 88, 253
 Thacker R. J., Tittle E. R., Pearce F. R., Couchman H. M. P., Thomas P. A., 2000, *MNRAS*, 319, 619
 Thomas P. A. et al. (the Virgo Consortium), 1998, *MNRAS*, 296, 1061
 Thomas P. A., Couchman H. M. P., 1992, *MNRAS*, 257, 11
 Thomas P. A., Muanwong O., Pearce F. R., Couchman H. M. P., Edge A. C., Jenkins A., Onuora L., 2001, *MNRAS*, in press (astro-ph/0007348)
 Tozzi P., Norman C., 2001, *ApJ*, 546, 63
 Valageas P., Silk J., 1999, *A&A*, 350, 725
 White S. D. M., Frenk C. S., 1991, *ApJ*, 379, 52
 White D. A., Jones C., Forman W., 1997, *MNRAS*, 292, 419
 Wu K. K. S., Fabian A. C., Nulsen P. E. J., 2000, *MNRAS*, 318, 889
 Xue Y.-J., Wu X.-P., 2000, *ApJ*, 538, 65